# Arup NSHM - Australian National Seismic Hazard Model

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## Abstract

An Australia-wide probabilistic seismic hazard analysis (PSHA) was developed for consideration in the Geoscience Australia National Seismic Hazard Assessment 2018 Project (Arup NSHM). The Arup NSHM source model uses the neotectonic domains of Clark et al. 2012 to derive b-values. Further sub-division of the neotectonic domains is used to derive a-values based on the observed spatial distribution of seismicity within each domain to derive seismic activity (a-value). Earthquake catalogue processing included aftershock removal and magnitude conversion. Completeness was calculated for each of the neotectonic domains. Earthquake recurrence curves were developed using Weichert's maximum likelihood approach (Weichert, 1980) and a minimum magnitude of M4.5. A logic tree was applied to capture the influence of epistemic uncertainty in the source characterisation and weight the two seismotectonic source models. The results of the PSHA are presented in terms of PGA and uniform hazard response spectra for the Sydney, Melbourne, Perth, Adelaide, and Brisbane.

**Keywords:** Australia probabilistic seismic hazard analysis

# 1 INTRODUCTION

This paper presents an Australia-wide probabilistic seismic hazard analysis (PSHA) for consideration in the Geoscience Australia National Seismic Hazard Assessment 2018 Project (Arup NSHM).

Probabilistic seismic hazard analyses combine seismic source zoning, earthquake recurrence and ground motion prediction equations to produce "hazard curves" in terms of level of ground motion and an associated annual frequency of being exceeded.

# 2 PROBABILISTIC SEISMIC HAZARD ANALYSIS METHODOLOGY

The methodology adopted is based on that originally proposed by Cornell (1968). Figure 1 shows the elements used to carry out the PSHA in this study:

1. A definition of the seismotectonic source zones that define the geographical variation of earthquake activity. These source zones are based on the distribution of observed seismic activity together with geological and tectonic factors and represent areas where the seismicity is assumed to be homogenous; i.e. there is an equal chance that a given earthquake will occur at any point in the zone.

2. An understanding of earthquake recurrence with respect to earthquake magnitude. Usually there are many more small low magnitude earthquakes than large, high magnitude earthquakes. Again observed seismicity is used to determine the earthquake recurrence relationships.

3. One or more ground motion prediction equations (GMPEs) or attenuation relationships are required to calculate expected ground motions at point A due to an earthquake of known magnitude within an area of uniform seismicity. Generally, attenuation relationships are derived from observations from past earthquakes.

The analyses presented here calculate the peak ground acceleration (PGA) and the uniform hazard response spectra (UHRS) for the given return period. The UHRS is a multi-parameter description of the ground motion generated from a PSHA. A response spectrum is particularly useful as it gives a direct indication of the peak response of a structure when it is subjected to an earthquake ground motion. It is usually plotted as a function of peak acceleration response against structural period, and a uniform hazard response spectrum is constructed so that all points on the spectrum have an equal probability of being exceeded during a defined period of exposure. The UHRS envelopes the contributions from a range of earthquakes that contribute to the seismic hazard. For example, the short period motion of a UHRS is usually dominated by contributions from small nearby earthquakes while the long period response is dominated by contributions from large distant earthquakes.

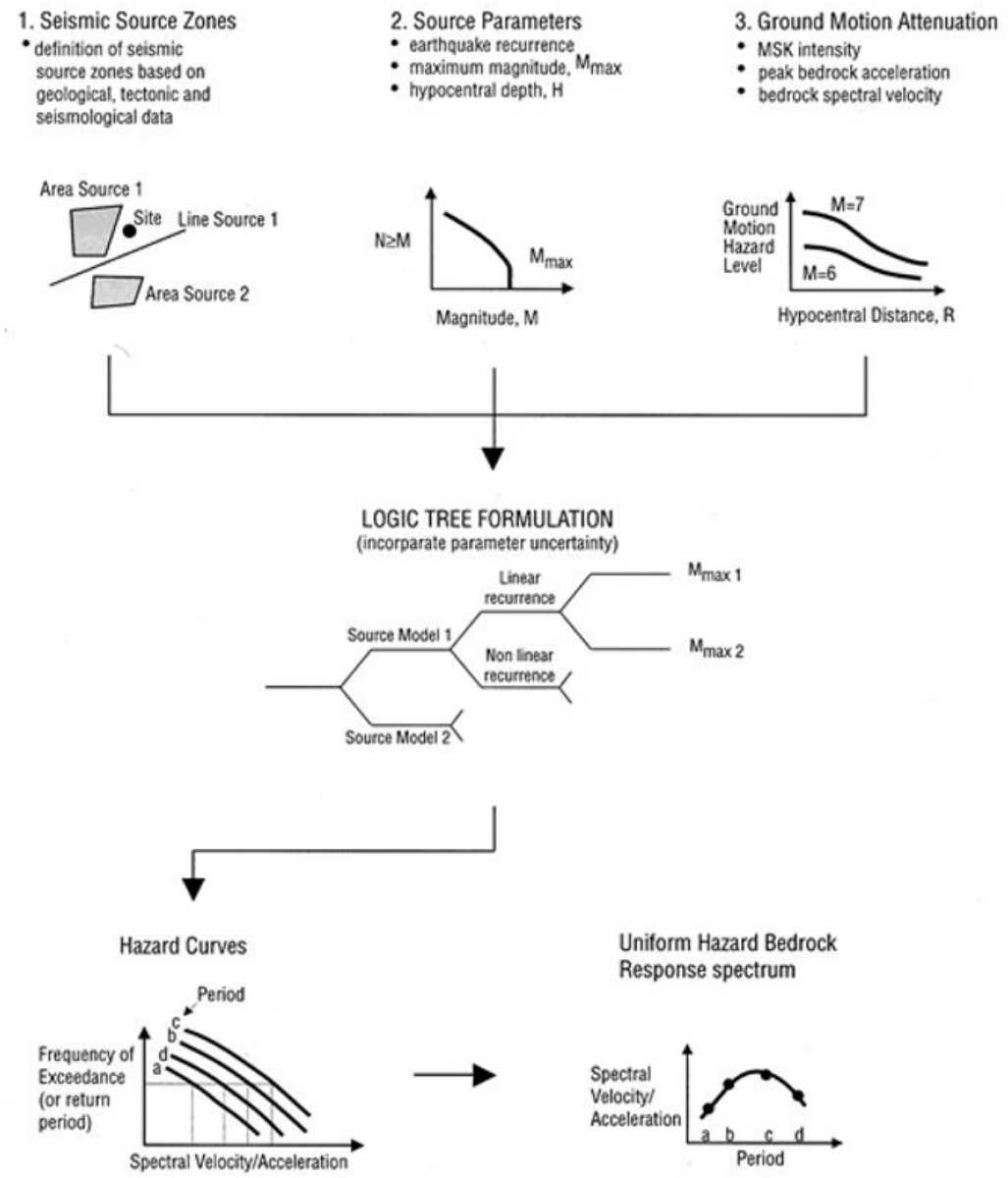


Figure 1 Probabilistic Seismic Hazard Analysis (PSHA) methodology

## 3 SEISMICITY/EARTHQUAKE CATALOGUE

The instrumental records were compiled from International Seismological Centre (ISC), EHB Bulletin in ISC and ISC-GEM Global Instrumental Earthquake Catalogue (ISC-GEM; Storchak et al., 2012). The ISC Bulletin contains records with a minimum magnitude of 3 from 1904 to 2017. The EHB earthquake catalogue is a groomed version of the ISC Bulletin with re-calculation of the location and depth of events from 1960 to 2013. The ISC-GEM Bulletin further refines the location, depth and magnitude based on the existing bulletin data including ISC and EHB. The historical events before 1900 were compiled from Gary Gibson and GA whom have catalogued records from 1837 to 1900.

### 3.1 Foreshock and Aftershock Removal

All earthquake catalogues contain some foreshock and aftershock sequences. Aftershocks are earthquake events, which occur after and in connection with a main event; similarly, foreshocks precede such main events. A declustering method of

modified version of Leonard (2008) (i.e. Method 3 recommended in Burbidge, 2012) has been adopted. This method is considered more appropriate for Australia than other decluttering algorithms (e.g. Gardner and Knopoff 1974) developed in tectonically active areas.

### 3.2 Magnitude Scale

As a result of the variety of sources used in the catalogue compilation, conversions to a uniform moment magnitude ($M_W$) scale was required. The body-wave magnitude ($m_b$), surface-wave magnitude ($M_S$) values and local magnitude ($M_L$) were converted to $M_W$.

The conversion of $M_S$ to $M_W$ used the following equation suggested in Scordilis (2006). The only two available ISC-GEM data consisting both $M_S$ and $M_W$ within the Australia region were used to show the conversion is consistent with the global dataset used by Scordilis 2006 (Figure 2)

$$M_W = 0.67M_S + 2.07, \text{ for } 3 < M_S \leq 6.1 \quad [1]$$
$$M_W = 0.99M_S + 0.08, \text{ for } 6.1 < M_S \leq 8.2 \quad [2]$$

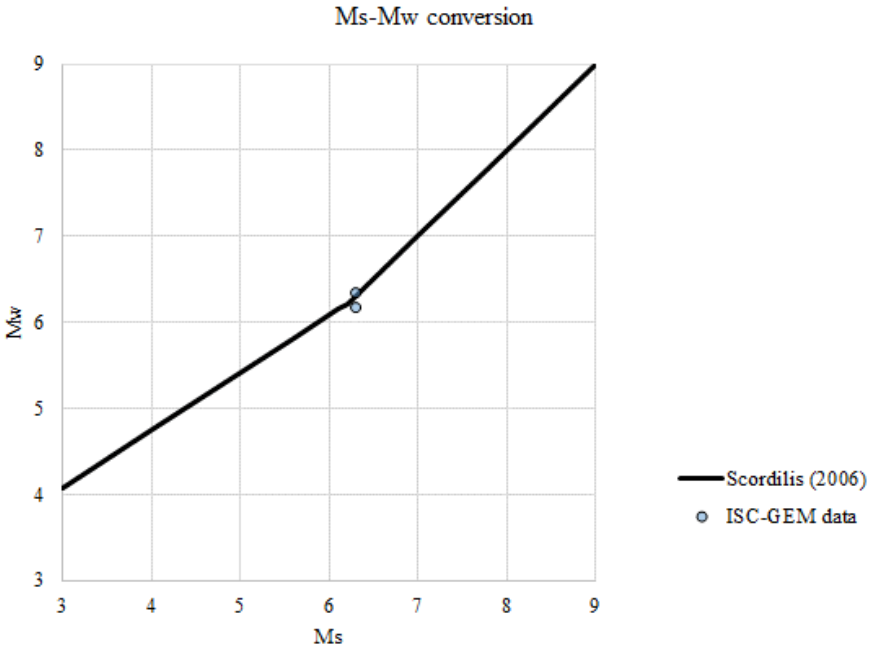


Figure 2 $M_S$-$M_W$ conversion (Scordilis, 2006)

Using the ISC catalogue of both $m_b$ and $M_W$ within the Australia region, a conversion for this study was developed by linear regression of the available data. The conversion has also been compared with both Scordilis (2006) and the Geoscience Australia model (Burbidge, 2012) (Figure 3),

$$M_W = 0.9864m_b + 0.3115 \quad [3]$$

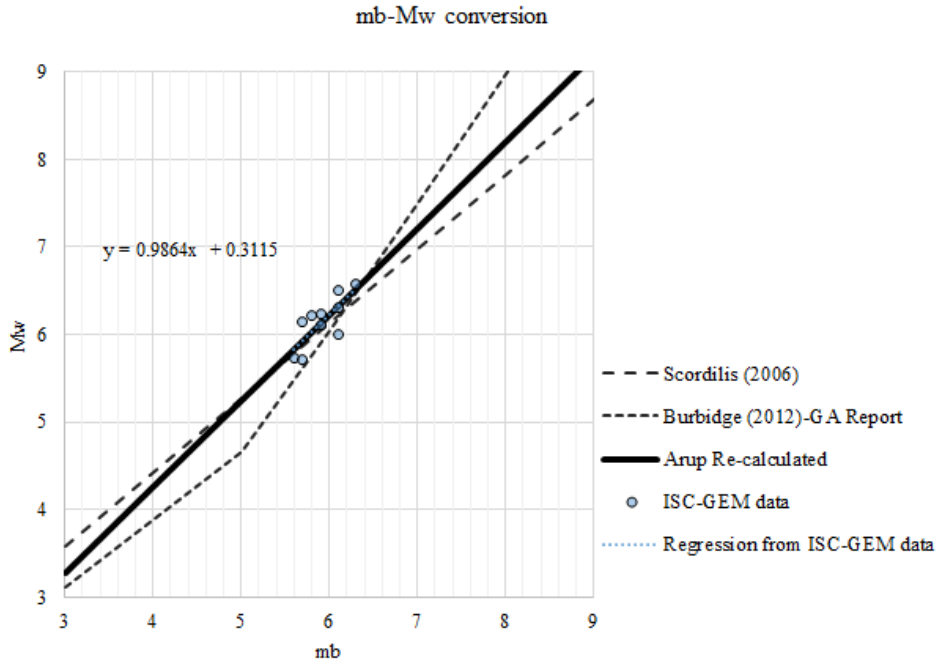


Figure 3 Earthquake magnitude $m_b$ to $M_W$ conversion relative to GA and Scordilis (2006)

Ghasemi et al. (2016) published 15 earthquakes with $M_W$ and $M_L$. By comparing these 15 earthquakes with the conversions shown in Allen et al. (2011), $M_L$ to $M_W$ conversion for this study was re-developed as follows (Figure 4):

$$M_W = 0.62M_L + 1.18, \text{ for } M_L \leq 5 \quad [4]$$

$$M_W = 0.62M_L + 0.5(M_L - 4.6) + 1.18, \text{ for } M_L > 5 \quad [5]$$

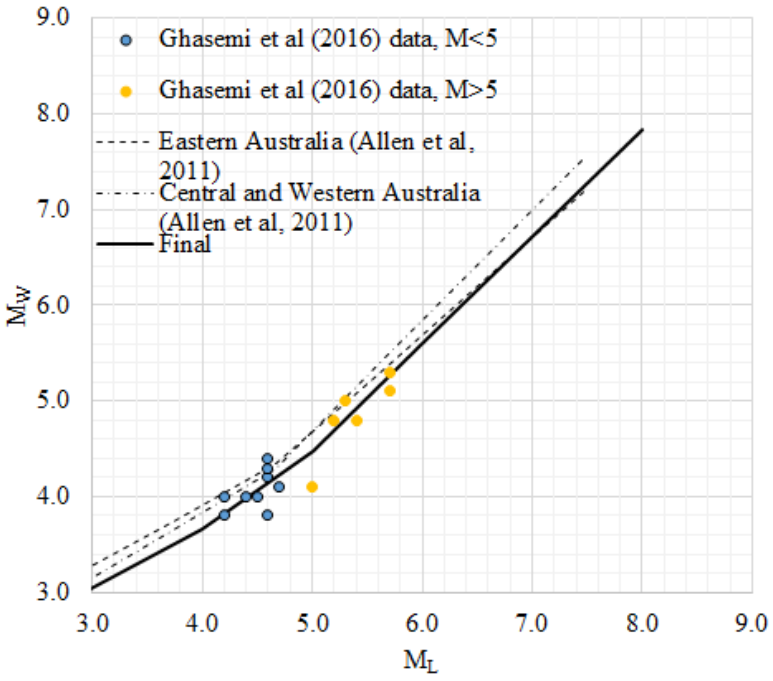


Figure 4 Earthquake magnitude $M_L$ to $M_W$ conversion relative to the 15 earthquake in Ghasemi et al. (2016) and Allen et al. (2011)

## 4 SEISMOTECTONIC SOURCE MODELS

A seismotectonic model was developed following the Neotectonic Domains of Clark et al. 2012 (Figure 5). The neotectonic domains characterise variation in fault scarp length, vertical displacement, proximity to other faults and relationship to topography. The Domains relate to a distinct underlying crustal type and architecture, broadly considered to represent cratonic, non-cratonic and extended environments. The larger domain areas allow a greater number of earthquakes to be considered and a more statistically meaningful calculation of recurrence rate (b-value).

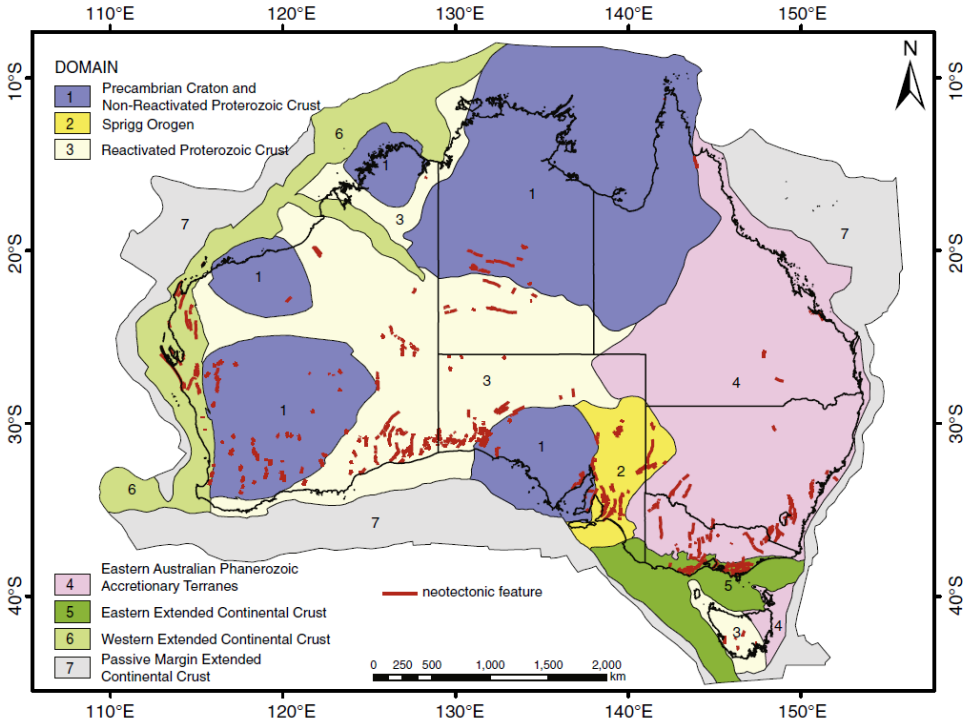


Figure 5 Neotectonic Domains from Clark et al. 2012

The Domain model is further subdivided based on the observed spatial distribution of seismicity (Figure 6). The Sub-domain source model captures the local partitioning or variation of seismic activity (a-value) within the zones. The Sub-domain model delineates areas of increased seismic activity such as the south west seismic zone (SWSZ) and the Flinders Range. The Sub-domain also partitions the seismicity on the east coast of Australia covering Sydney, Melbourne and Brisbane.

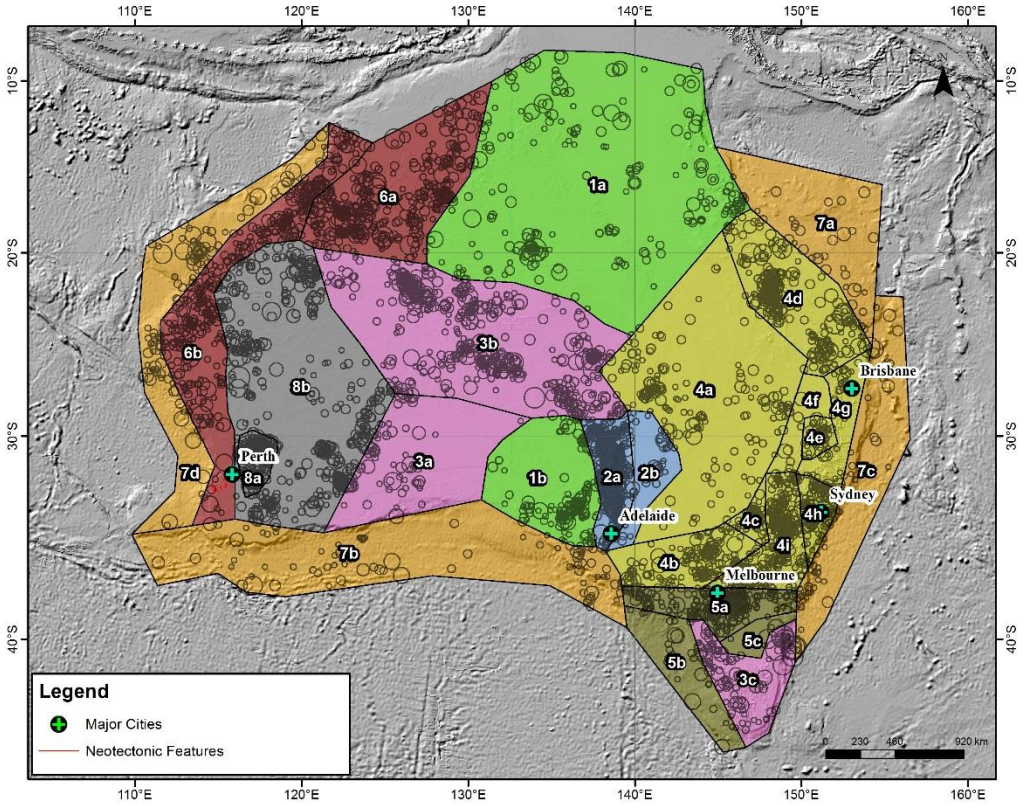


Figure 6 Arup Sub-Domain source model.

## 5 SEISMIC SOURCE PARAMETERS

### 5.1 Catalogue Completeness

The accurate estimation of the earthquake recurrence parameters requires an assessment of the completeness of the independent earthquake catalogue. The statistical completeness of the catalogue has been assessed by analysing the variations in recorded earthquake activity over time. As the earthquake recurrence potentially varies across the Australia region due to the variation of stress field and tectonic setting, the completeness of the earthquake catalogue has been calculated for each Domain, respectively. Figure 7 shows the activity rate of Domain 4 over time on a log-log scale. A horizontal line, corresponding to a magnitude range, implies a constant earthquake recurrence rate over time. When the line has a break in slope, the recurrence rate has changed and therefore the catalogue is not complete. Completeness intervals for respective converted $M_W$ magnitude ranges are assigned to the years before present at the break in horizontal slope on the right end of the graph (vertical lines). The earthquake completeness intervals determined for all Domains are presented in Table 1.

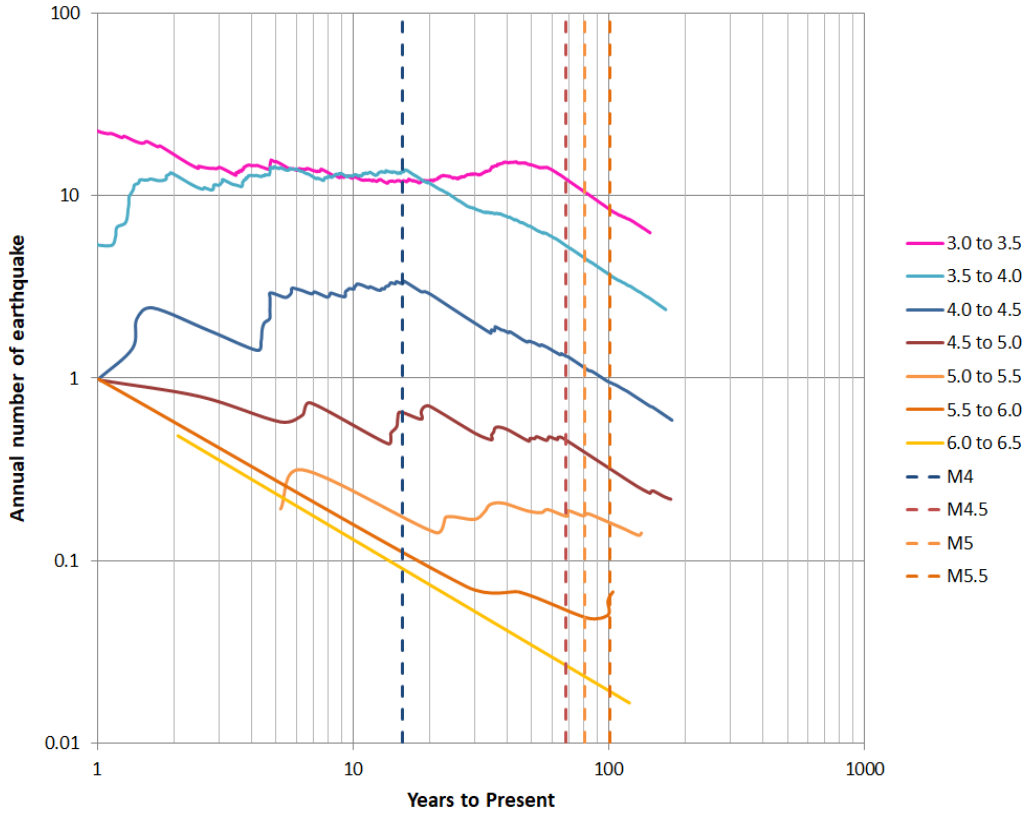


Figure 7 Completeness Intervals of Domain 4

Table 1 Earthquake catalogue completeness intervals for each Domain

| Domain | M3.0-3.5 | M3.5-4.0 | M4.0-4.5 | M4.5-5.0 | M5.0-5.5 | M5.5-6.0 | M6.0-6.5 |
|---|---|---|---|---|---|---|---|
| Domain 1 | 1987 | 1987 | 1987 | 1960 | 1960 | | |
| Domain 2 | 2002 | 2002 | 2002 | 2002 | 1937 | | |
| Domain 3 | 2002 | 2002 | 2002 | 1960 | 1900 | 1900 | 1900 |
| Domain 4 | 2002 | 2002 | 2002 | 1950 | 1937 | 1917 | |
| Domain 5 | 1972 | 1960 | 1960 | 1960 | 1900 | | |
| Domain 6 | 1995 | 1995 | 1972 | 1972 | 1937 | 1917 | 1917 |
| Domain 7 | 1995 | 1995 | 1967 | 1967 | | | |
| Domain 8 | 1987 | 1987 | 1965 | 1965 | 1965 | | |

## 5.2 Recurrence

The rate of occurrence of earthquakes in each area zone is described in terms of magnitude recurrence relationships in the form of the 'Gutenberg-Richter' relationship (Gutenberg and Richter, 1944):

$$\text{Log}_{10}\, N = a - b\,(M_W > 4) \qquad [6]$$

where N is the annual number of earthquakes greater than magnitude $M_W$, $a$ is the activity rate defined as the annual number of earthquakes greater than magnitude 4.0 and $b$ is the slope of the recurrence relationship. The complete part of the earthquake catalogue together with the equation above are used to compute a-value (activity rate) and b-value for each source zone through application of Weichert's maximum likelihood approach (Weichert, 1980).

Table 2 and shows the best estimate of b- value and a-value (activity M >4) derived for the Domain model. For each Sub-domain, the b-values are assigned from the respective parent Domain as per Table 2. The a-values are calculated from the observed activity within each Sub-domain. If the calculated activity density of the Sub-domain is less than the activity density of the parent Domain, each activity is weighted at 50%.

The standard deviation of the a- and b-value of each Domain model is approximately between 3% and 6%. To capture the variability, a general upper and lower bound were taken to be ±5% of the mean value. In some Sub-domains, the upper and lower bounds on b-values curves were manually refined to fit the observed seismicity.

Table 2 shows the best estimate of b-value and activity derived for the Domain and Sub-Domain models. Figure 8 shows the recurrence curve for Domain 4 and Sub-domain 4e as one example.

Table 2 Recurrence –Domain and Sub-Domain Models

| **Domain** | **Sub-Domain** | **b-value** | **Activity $M_W \geq 4$** |
|---|---|---|---|
| Domain 1 | | 0.95 | |
| | Sub-Domain 1a | | 1.2 |
| | Sub-Domain 1b | | 0.38 |
| Domain 2 | | 1.2 | |
| | Sub-Domain 2a | | 2.4 |
| | Sub-Domain 2b | | 0.65 |
| Domain 3 | | 0.9 | |
| | Sub-Domain 3a | | 0.695 |
| | Sub-Domain 3b | | 3 |
| | Sub-Domain 3c | | 0.28 |
| Domain 4 | | 1.1 | |
| | Sub-Domain 4a | | 1.59 |
| | Sub-Domain4b | | 0.405 |
| | Sub-Domain4c | | 0.0625 |
| | Sub-Domain4d | | 3.1 |
| | Sub-Domain4e | | 0.24 |
| | Sub-Domain4f | | 0.15 |
| | Sub-Domain4g | | 0.16 |
| | Sub-Domain4h | | 0.43 |
| | Sub-Domain4i | | 0.36 |
| Domain 5 | | 1.0 | |
| | Sub-Domain 5a | | 1.00 |
| | Sub-Domain 5b | | 0.38 |
| | Sub-Domain 5c | | 0.095 |
| Domain 6 | | 0.9 | |
| | Sub-Domain 6a | | 1.7 |
| | Sub-Domain 6b | | 1.41 |
| Domain 7 | | 0.8 | |
| | Sub-Domain 7a | | 0.28 |
| | Sub-Domain 7b | | 0.58 |
| | Sub-Domain 7c | | 0.19 |
| | Sub-Domain 7d | | 1.2 |

| Domain | Sub-Domain | b-value | Activity $M_W \geq 4$ |
|---|---|---|---|
| Domain 8 | | 0.8 | |
| | Sub-Domain 8a | | 1.05 |
| | Sub-Domain 8b | | 2.525 |

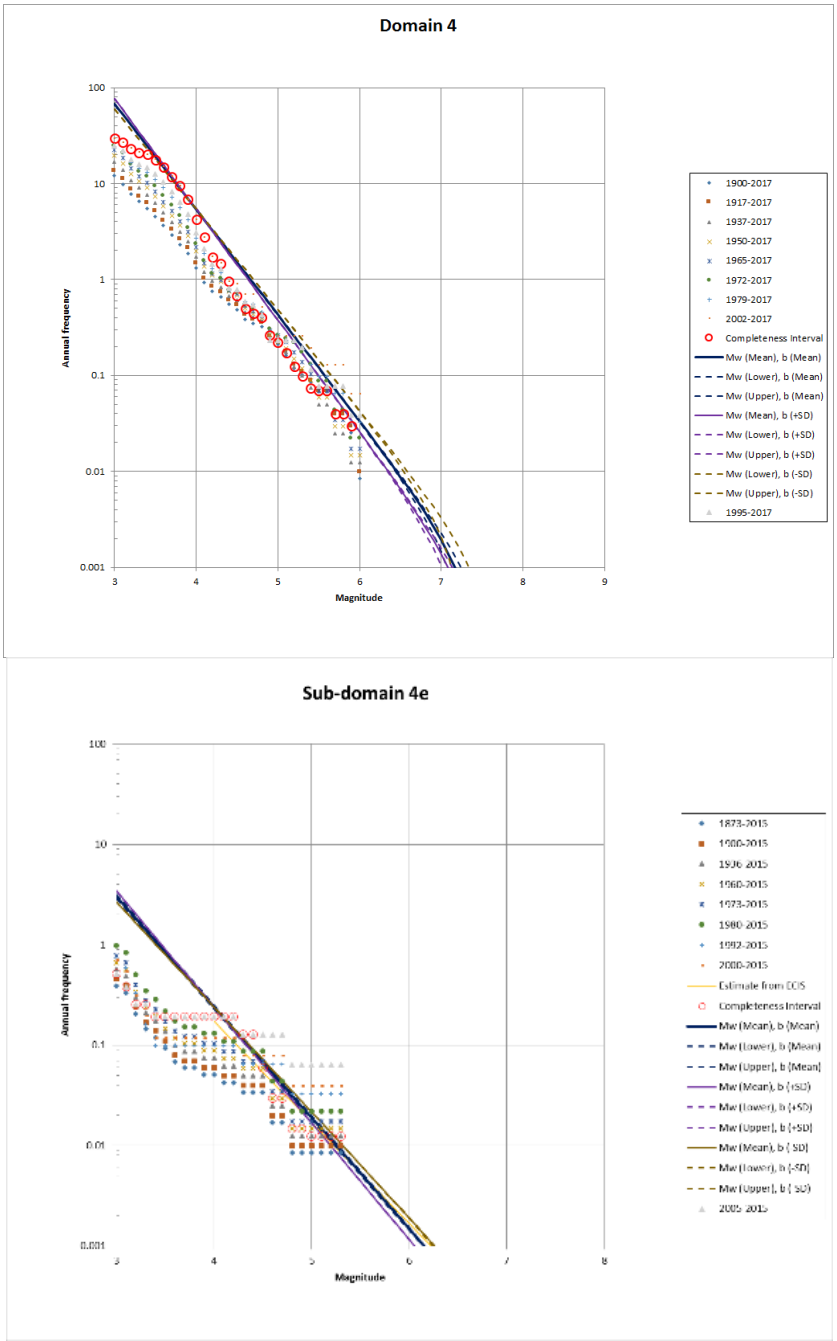


Figure 8 Recurrence curves for Domain 4 and Sub-domain 4e.

## 5.3 Minimum and Maximum Magnitudes

A minimum magnitude of $M_W$4.5 has been adopted for this PSHA on the basis that the likelihood of an earthquake of smaller magnitude causing damage to engineered structures can be reasonably discounted. Additionally, adoption of a lower minimum magnitude may unrealistically increase the level of high-frequency (low-period) ground motions determined in the analysis.

Maximum magnitudes are assigned corresponding to the Neotectonic Domains in Leonard et al. 2014 (Table 3).

Table 3 Maximum Magnitudes

| Zone | $M_{max}$ | Weight | $M_{max}$ - LB | Weight | $M_{max}$ - UB | Weight |
|---|---|---|---|---|---|---|
| Domain 1 | 7.30 | [0.80] | 7.10 | [0.10] | 7.50 | [0.10] |
| Domain 2 | 7.50 | [0.80] | 7.30 | [0.10] | 7.70 | [0.10] |
| Domain 3 | 7.60 | [0.80] | 7.40 | [0.10] | 7.80 | [0.10] |
| Domain 4 | 7.50 | [0.80] | 7.30 | [0.10] | 7.70 | [0.10] |
| Domain 5 | 7.40 | [0.80] | 7.20 | [0.10] | 7.60 | [0.10] |
| Domain 6 | 7.70 | [0.80] | 7.50 | [0.10] | 7.90 | [0.10] |
| Domain 7 | 7.50 | [0.80] | 7.30 | [0.10] | 7.70 | [0.10] |
| Domain 8 | 7.30 | [0.80] | 7.10 | [0.10] | 7.50 | [0.10] |

### 5.4 Focal Depth Distribution

The focal depth distribution observed within the independent earthquake catalogue has been considered for the areal source zones and the subduction sources (Table 4).

Table 4 Focal Depth Distribution – Areal Source Zones

| Depth Range | Weight |
|---|---|
| 0 - 10km | [0.80] |
| 10 - 20km | [0.20] |

## 6 GROUND MOTION PREDICTION EQUATIONS (GMPEs)

Ground Motion Predication Equations (GMPEs) describe the median predicted gorund motion at a site form an earthquake with a given magnitude and distance from the hypocentre. These ground-motion models are derived based on an analysis of the records applicable to Australia and analogue regions.

GMPEs for horizontal ground motions at a range of spectral periods have been used in this study and align with Leonard et al. 2014 (Table 5).

Table 5 Ground Motion Prediction Equations

| Source Zone | GMPEs | Weight |
|---|---|---|
| Domains 1, 3, 8 | Allen et al. (2012) | [0.30] |
| | Somerville et al. (2009) (Yligarn Craton) | [0.30] |
| | Atkinson and Boore (2006) | [0.30] |
| | Chiou and Youngs (2014) | [0.10] |
| **Source Zone** | **GMPEs** | **Weight** |
| Domains 2, 4, 5,6,7 | Allen et al. (2012) | [0.25] |
| | Somerville et al. (2009) (Non-Craton) | [0.25] |
| | Atkinson and Boore (2006) | [0.25] |
| | Chiou and Youngs (2014) | [0.25] |

## 7 LOGIC TREE

The logic tree developed for this study considers the seismotectonic source model with weights given to parameters to capture the influence of epistemic uncertainty (Figure 9).

- Allowance for variation in the a- and b-value in all areal sources has been incorporated in the seismic model by assigning weights of 0.7, 0.15 and 0.15 to the mean and mean ± sigma of value respectively as presented in Tables 3 and 4.
- Allowance has been made for variability of maximum magnitude in the different areal zones by attributing weights to $M_{max}$ (Table 3).
- Variation of focal depth has been captured through two depth distributions (Table 4).
- GMPEs have been assigned weights according to their applicability in each of the tectonic environments (Table 5).

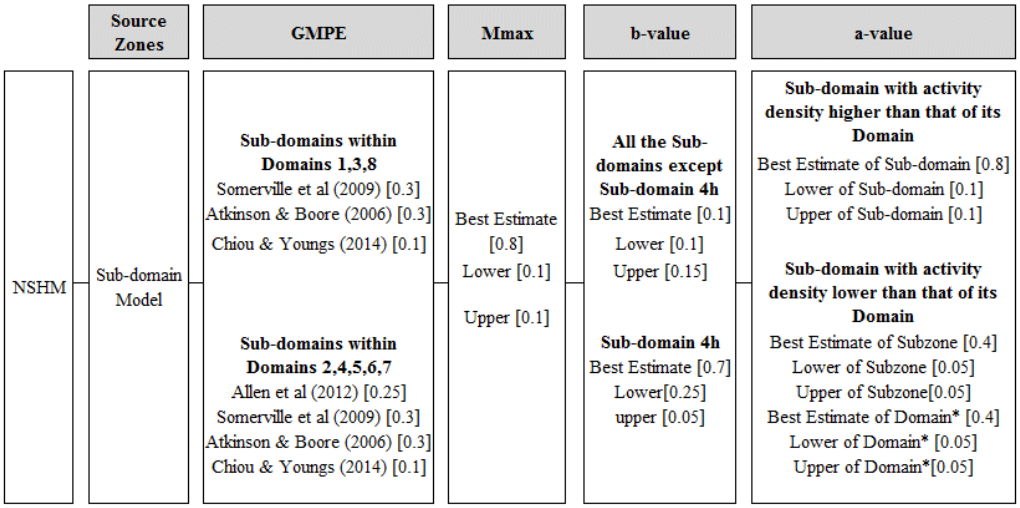


Figure 9 Logic Tree

## 8 PSHA GROUND MOTION RESULTS

### 8.1 Peak Ground Acceleration

The PSHA results for PGA in bedrock at Sydney, Melbourne, Brisbane, Perth and Adelaide are presented in Table 6.

Table 6 Peak Ground Acceleration for 1/1500 and 1/2500 for select cities

| | **Peak Ground Acceleration (g)** | |
|---|---|---|
| | **1/500 annual exceedance probability** | **1/2500 annual exceedance probability** |
| Sydney | 0.06 | 0.18 |
| Melbourne | 0.07 | 0.20 |
| Brisbane | 0.02 | 0.06 |
| Perth | 0.08 | 0.20 |
| Adelaide | 0.09 | 0.24 |

## 8.2 Magnitude Distance Deaggregation

Figure 10 presents a magnitude-distance deaggregation plot for PGA 1/2500 in Sydney

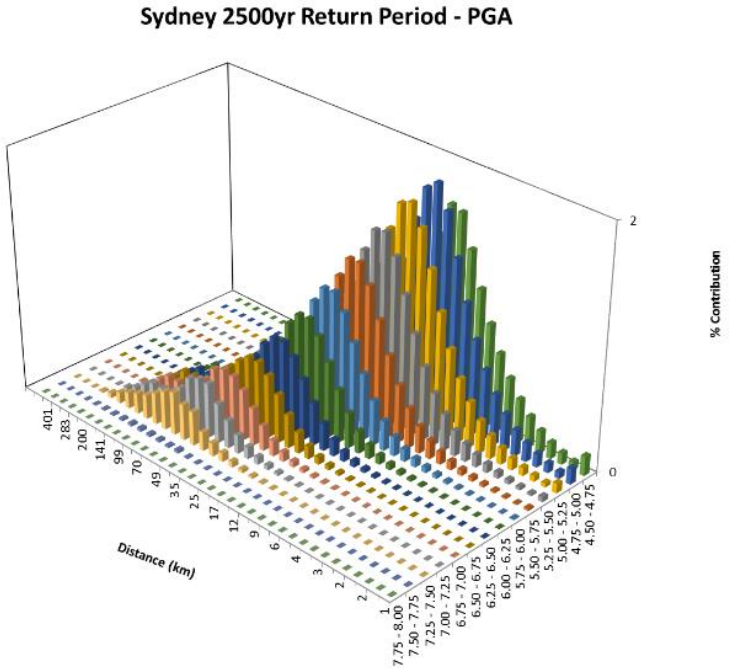


Figure 10 Magnitude-Distance Deaggregation Plot for PGA 1/2500 in Sydney

## 8.3 Response Spectra

The results of the PSHA are presented in terms of horizontal peak ground acceleration and uniform hazard response spectra (UHRS) assuming 5% structural damping at bedrock for select cities. The results are presented for two earthquake return periods (Figure 11):

- 1/500 annual exceedance probability
- 1/2,500 annual exceedance probability

As mentioned in the Burbidge (2012), the $V_{S30}$ of the GMPEs of Somerville et al. (2009) and Allen (2012) are both calibrated to 865 and 820m/s. For other GMPEs, the $V_{S30}$ of 760m/s was adopted in this study. As such, the response spectra refer to bedrock with $V_{S30}$ ranged from 760 to 865m/s.

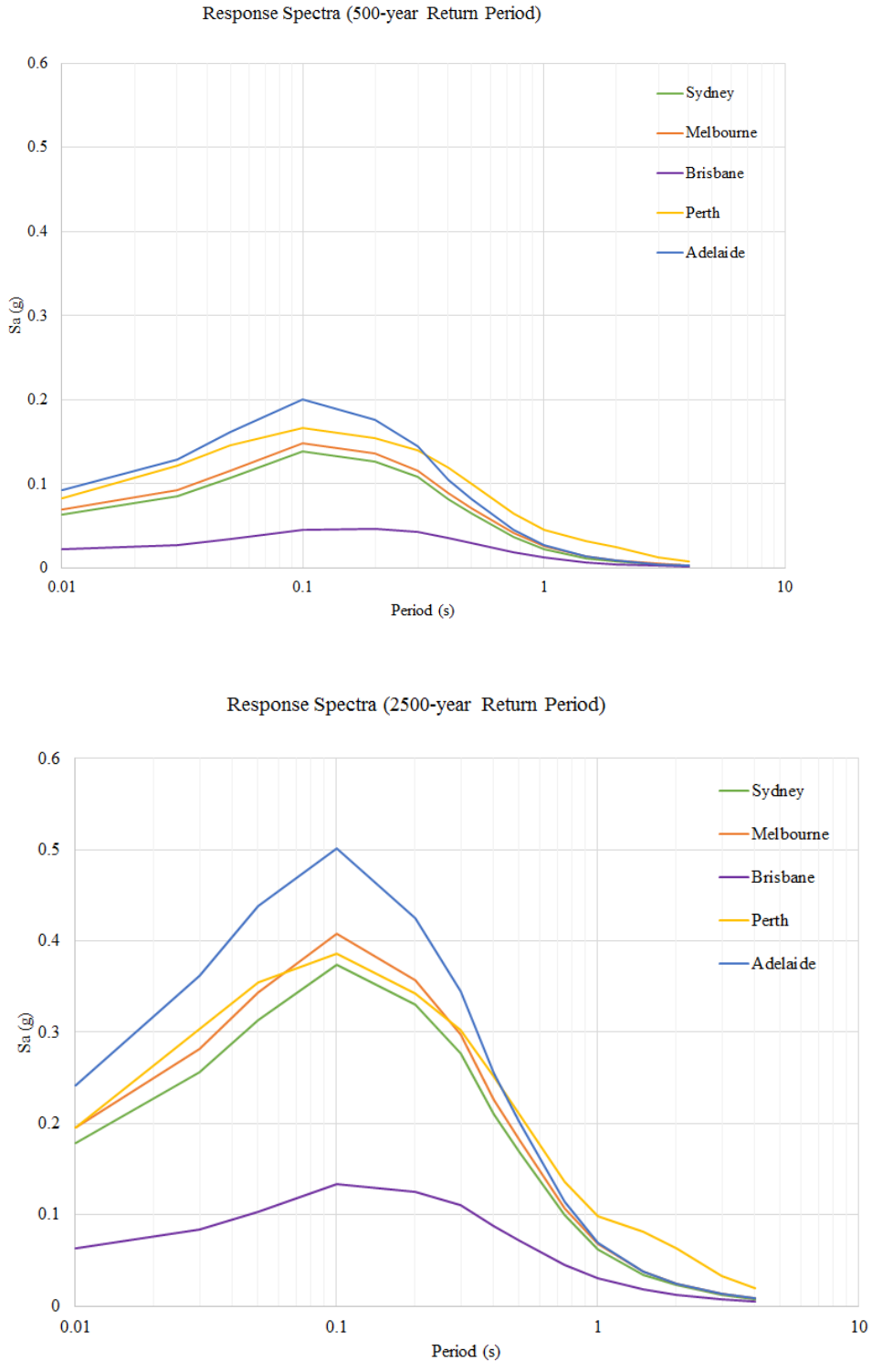


Figure 11 Response Spectra of various Australian Capitals at Rock Sites

## 9 Summary and Discussion

An Australia-wide probabilistic seismic hazard analysis was completed for consideration in the Geoscience Australia National Seismic Hazard Assessment 2018 Project (Arup NSHM). The model was originally submitted to Geoscience Australia prior to an Expert Elicitation Workshop held in March 2017. This paper presents a revised version of the model considering comments and discussion following the workshop.

The Arup NSHM source model uses the neotectonic domains of Clark et al. 2012 to derive b-values. Further sub-division of the neotectonic domains is used to derive a-values based on the observed spatial distribution of seismicity within each domain to derive seismic activity (a-value). The Domains capture a very broad scale of tectonic setting which allow a sufficient numbers of earthquake to calculate the seismic parameters (e.g. b-value), while the Sub-Domains capture the change of local tectonic and variation of seismicity.

Earthquake catalogue processing included magnitude conversion and aftershock removal. The magnitude conversion was developed with earthquake data within the Australia region. The declustering method of modified version of Leonard (2008) (i.e. Method 3 recommended in Burbidge, 2012) was applied.

Completeness was calculated for each of the neotectonic domains. Earthquake recurrence curves were developed using Weichert's maximum likelihood approach (Weichert, 1980) and a minimum magnitude of M4.5.

A logic tree captured the influence of epistemic uncertainty in the source characterisation and weight the two seismotectonic source models.

Neotectonic features (active faults) are not explicitly incorporated in this model. Site-specific studies proximal to known neotectonic feature that consider hazard at longer annual exceedance probabilities (e.g. greater than 1/2500) should incorporate these sources.

The results of the PSHA are presented in terms of PGA and uniform hazard response spectra for the Sydney, Melbourne, Perth, Adelaide, and Brisbane.

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